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PERFORMANCE OF COMPRESSOR-TURBINE

JET-PROPULSION SYSTEMS

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NACA

WASHINGTON

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

ADVANCE CONFIDENTIAL REPORT

PERFORMANCE OF COMPRESSOR-TURBINE JET-PROPULSION SYSTEMS

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SUMMARY

An analysis of the performance of compressor-turbine jet-propulsion systems was carried out by calculating the thrust power from a compressor-turbine jet engine with a systematic variation of pressure ratio, fuel-air ratio, compressor and turbine efficiencies, flight speed, altitude, and maximum gas temperature.

Increasing the compressor and turbine efficiencies from 70 to 80 percent was found to double the over-all efficiency of the engine at 300 miles per hour (440 fps). Increasing the speed from 300 to 600 miles per hour (880 fps) increased the over-all efficiency by 7 to 10 percent. The maximum power output at a particular altitude was shown to be approximately proportional to the temperature difference between the combustion chamber and the free atmosphere.

INTRODUCTION

The basic principles of thermal-air jet propulsion have long been understood but not until recently have systems been devised that are capable of applying these principles to the propulsion of passenger-carrying airplanes. The method that appears to have the greatest potentialities makes use of mechanical compression of atmospheric air and continuous burning of fuel in the compressed air. One of the early practicable systems, the Italian Caproni-Campini, made use of an ordinary internal-combustion engine for running the compressor.

This system eliminated the propeller but still had the heavy weight and the complication of the reciprocating engine combined with the low efficiency of a marginal jet-propulsion system.

The use of a gas turbine for driving the compressor offered the advantages of simplicity and low engine weight per horsepower output, but the thermal efficiency was impracticably low because the turbine had to operate at low temperatures to prevent blade damage. Brown, Boveri & Company, Limited, had developed practical gas-turbine power plants for stationary installations, in which weight was no problem and a considerable amount of regeneration could be used. The thermal-air jet engine with turbine-driven compressor became a practical means of aircraft propulsion, however, only with the development of materials for gas-turbine rotor blades that could operate continuously at temperatures of 1200° F or higher and the development of a light-weight rotary compressor capable of giving a pressure ratio of at least 3, at greater than 60 percent efficiency. Reference 1 describes a turbine-compressor unit suitable for use in a jet engine.

Although the temperatures and efficiencies at which the turbine-compressor jet engine becomes practicable are of interest, it appears more important to inquire into the effect of further improvement in temperatures, efficiencies, and other pertinent factors in jet-engine performance. An analysis of the effects of various jet-engine design and operational parameters may indicate the most profitable lines of developmental research and the amount of improvement in performance and efficiency to be expected from such research. Such an analysis of jet-engine performance is presented herein. The altitude and speed of flight, the turbine and compressor efficiencies, the fuel-air and pressure ratios, and the combustion-chamber temperature are varied to show the effect of each not only on the engine thrust power but also on the optimum values of the other parameters. Among the pertinent topics not considered in this analysis are engine weights and the effect of arbitrarily changing the fuel rate for a particular power plant.

METHOD OF ANALYSIS

The calculations for this study were made on a Mollier chart for air (see fig. 1, which was transformed from a chart in reference 2 and is placed at the end of the report) by the methods described in reference 3. For purposes of this analysis, air compression by ram is isentropic, mechanical compression is at an arbitrarily assigned efficiency, combustion takes place at constant pressure and a given efficiency, energy is taken from the working fluid by the turbine at an arbitrarily assigned efficiency, and the air after passing the turbine accelerates isentropically to free-stream static pressure.

For every combination of altitude, speed, and maximum allowable temperature, various pressure ratios are used; in each case the amount of fuel required to raise the air temperature to the defined maximum is burned. For each set of conditions two combinations of fuel-air ratio and pressure ratio are stressed - one giving maximum power and one giving maximum over-all efficiency.

The calculations on the Mollier chart indicate the thrust power from each pound per second of conducted air. In order to show more clearly the effects of altitude and speed, the design is assumed to be such that the weight flow of charge air is proportional to the free-stream stagnation density; the base used is 40 pounds per second at 800 feet per second at sea level. (See fig. 2.) This assumption is in reasonable accord with results from actual installations because the air velocity should be approximately constant in the engine in order to maintain the compressor and turbine efficiencies. Whenever possible, the graphs of results are drawn with scales of both power and power per (pound per second) of charge air. The graphs for zero flight speed at sea level show the static thrust force; for all other conditions, power rather than thrust is shown.

The compressor and turbine are operating at defined efficiencies so that, when the fuel-air ratio and the compression ratio are changed at a particular altitude and speed, the curves represent an infinite number of engines, each of which is designed to have the defined efficiencies at the particular operating conditions under consideration.

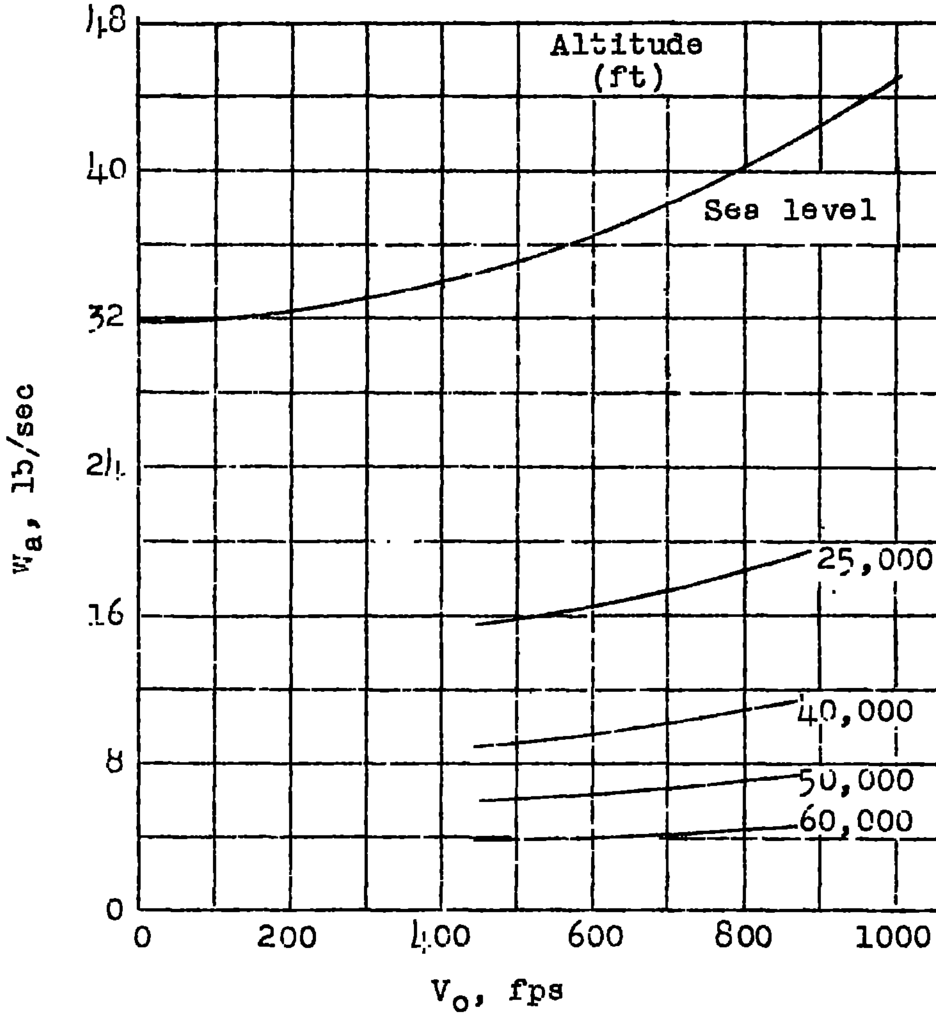


Figure 2.- Weight flow of charge air.

The results of the analysis are presented in two parts. In the first part only the jet engine is considered, without reference to any airplane in which it might be installed, and in the second part the performance of a particular installation is discussed.

The symbols used herein are defined in appendix A, and the conditions and assumptions used are discussed in appendix B.

PERFORMANCE OF JET ENGINE

Figure 3 presents a set of cycles on the Mollier chart for the purpose of illustrating the effect of pressure ratio and fuel-air ratio on the thrust from 1 pound of air. The vertical distances (enthalpy changes) in cycle B are significant in the following manner: The distance 0 to 1 indicates the velocity with which the air approaches the engine, 1 to 2 shows the energy added by the compressor, and 2 to 3 shows the energy added by burning fuel at constant pressure. At a particular altitude, flight speed, compressor efficiency, and maximum temperature (temperature at point 3), the location of point 2 uniquely determines the fuel-air ratio and the pressure ratio, so that one ratio may be plotted as a function of the other. The distance 3 to 4 shows energy taken out by the turbine, and 4 to 5 indicates the exit velocity of the propelling jet. The distance 5 to 5' is the same as 0 to 1 so that, when point 4 falls on 5', the

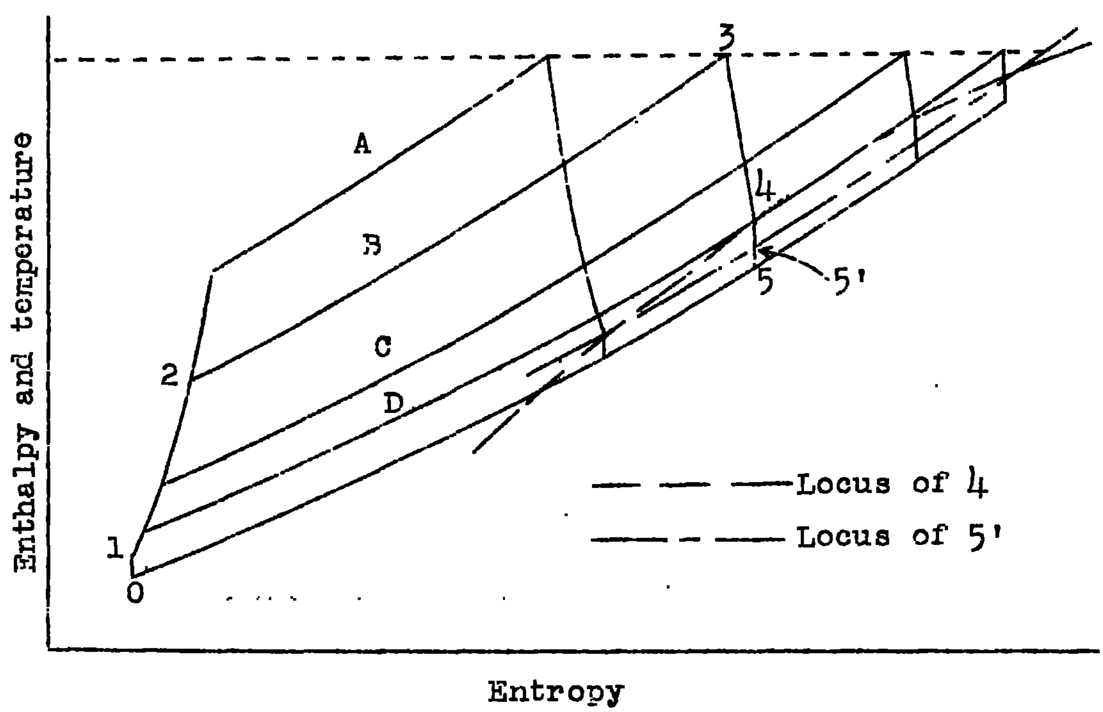


Figure 3.- Jet-engine cycles.

exit velocity equals the approach velocity and the conducted air contributes neither thrust nor drag. The thrust is, therefore, determined by the distance 4 to 5', which in conjunction with 0 to 1 shows the velocity increase of the conducted air; that is,

$$\text{Thrust} \propto \Delta V$$
$$\propto \sqrt{\text{Distance 4 to 5}} - \sqrt{\text{Distance 5' to 5}}$$

Cycle A, which has high pressure ratio and low fuel-air ratio, and cycle D, which has low pressure ratio and high fuel-air ratio, show little or no thrust. Cycles B and C give about equal thrust; and maximum thrust would be obtained with a cycle intermediate to B and C.

Figures 4 to 6 show the variation of thrust power with fuel-air ratio for various turbine and compressor efficiencies. The pressure-ratio curve is also shown as a function of fuel-air ratio. In order to find the pressure ratio for a particular point on a thrust-power curve, read the value of R for the fuel-air ratio corresponding to the point on the thrust curve. With the maximum temperature fixed, operation is possible only in a narrow range of fuel-air ratio and pressure ratio. These fuel-air and pressure ratios are shown for three gas temperatures in the following table:

Maximum temperature (°F)	Pressure ratio	Fuel-air ratio
1500	5 to 6	0.015 to 0.013
1800	8 to 9	.019 to .016
2100	10 to 12	.022 to .020

In this table both turbine and compressor efficiencies are about 80 percent. If these efficiencies were 70 percent, the fuel-air ratios would be 0.001 to 0.002 higher, and the pressure ratios would be about two-thirds of those shown. Decreasing the turbine and compressor efficiencies not only causes a decrease in the maximum power obtainable but also considerably restricts the range of fuel-air ratio for which operation is possible. This fact is particularly evident in figure 4. If the turbine efficiency is held constant and the compressor efficiency is varied, the power curves are quite similar to those shown.

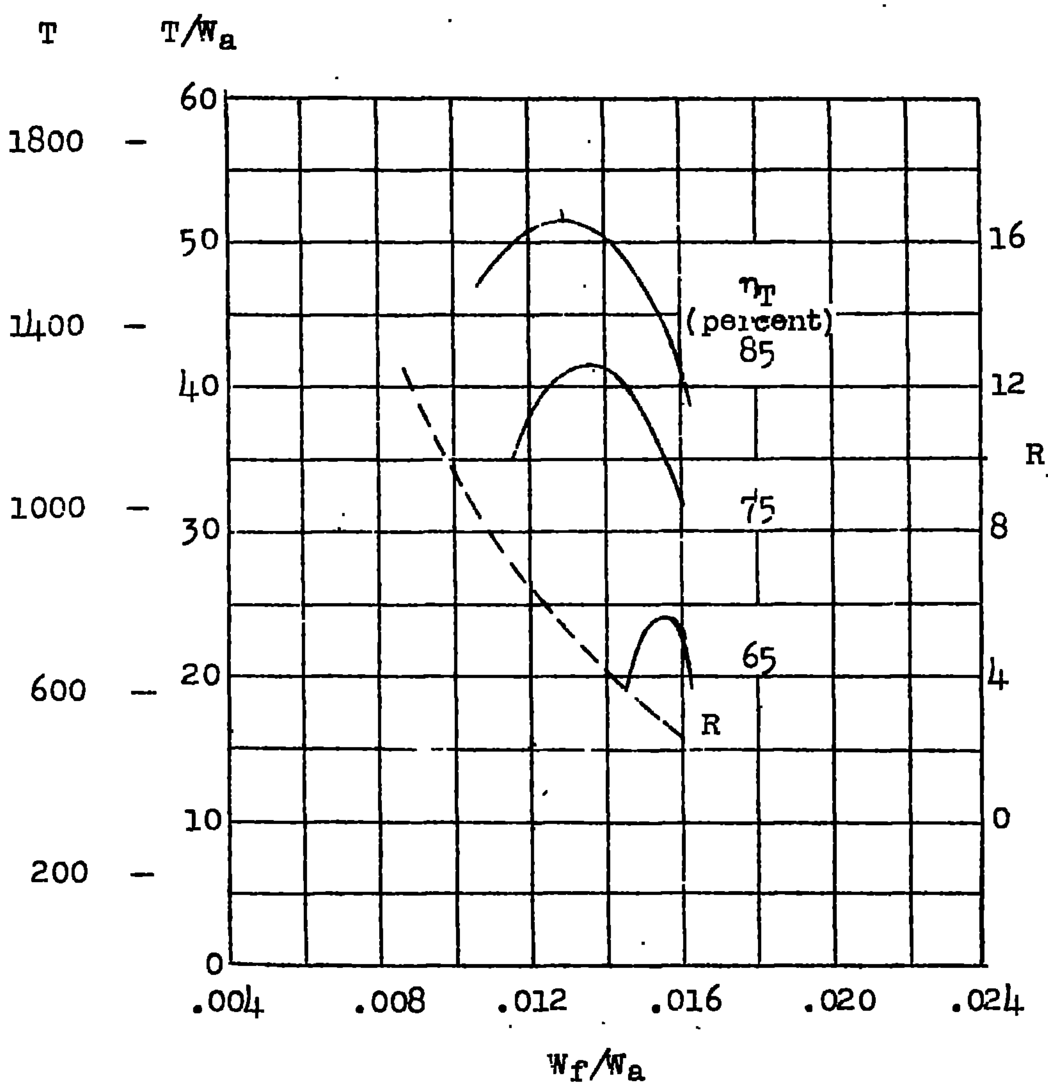


Figure 4.- Effect of fuel-air ratio on thrust and pressure ratio. At sea level; $V_o = 0$; $t_{max} = 1500^{\circ}$ F; $\eta_c = 75$ percent.

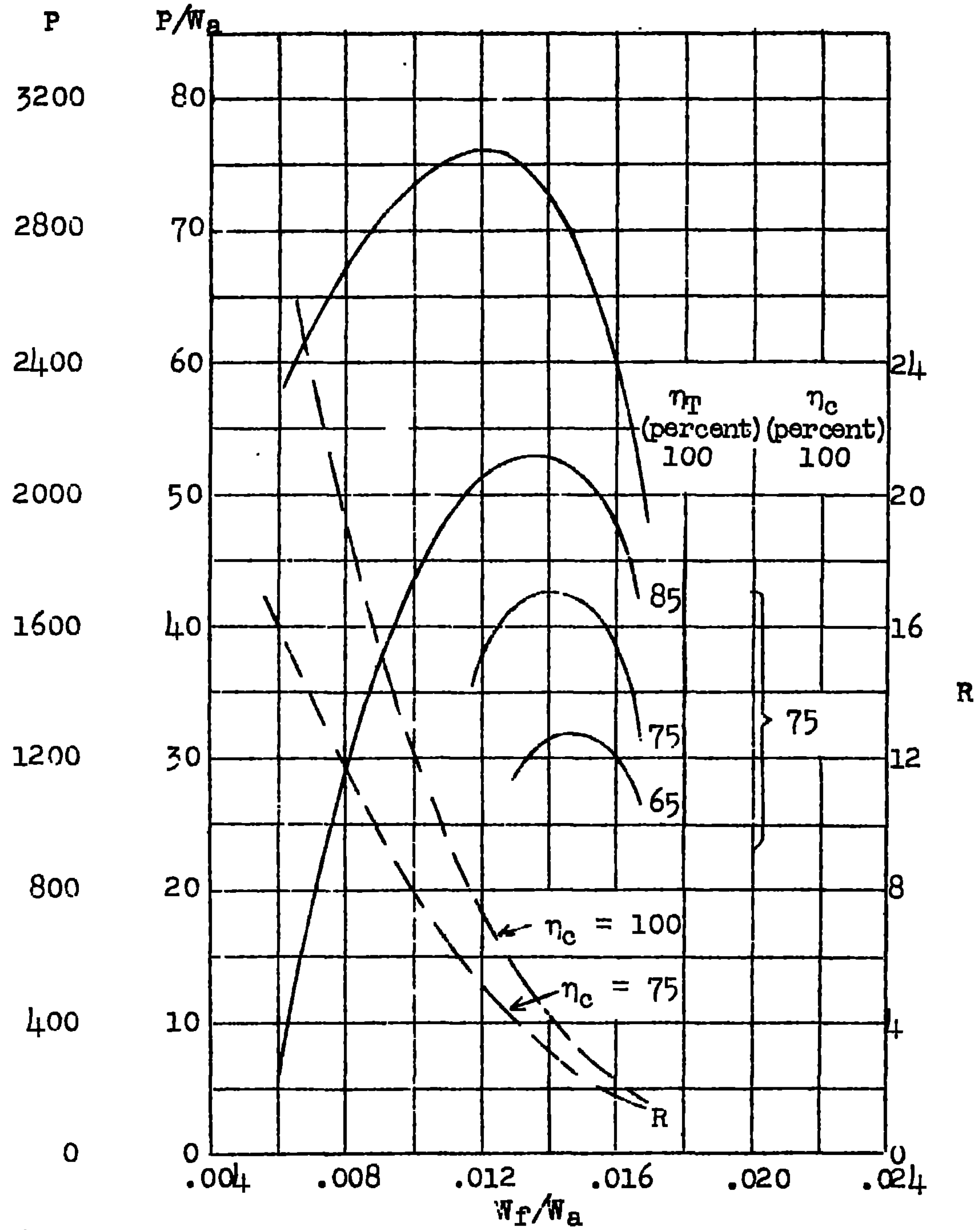


Figure 5.- Effect of fuel-air ratio on thrust power and pressure ratio. At sea level; V_o = 800 feet per second; t_{max} = 1500° F.

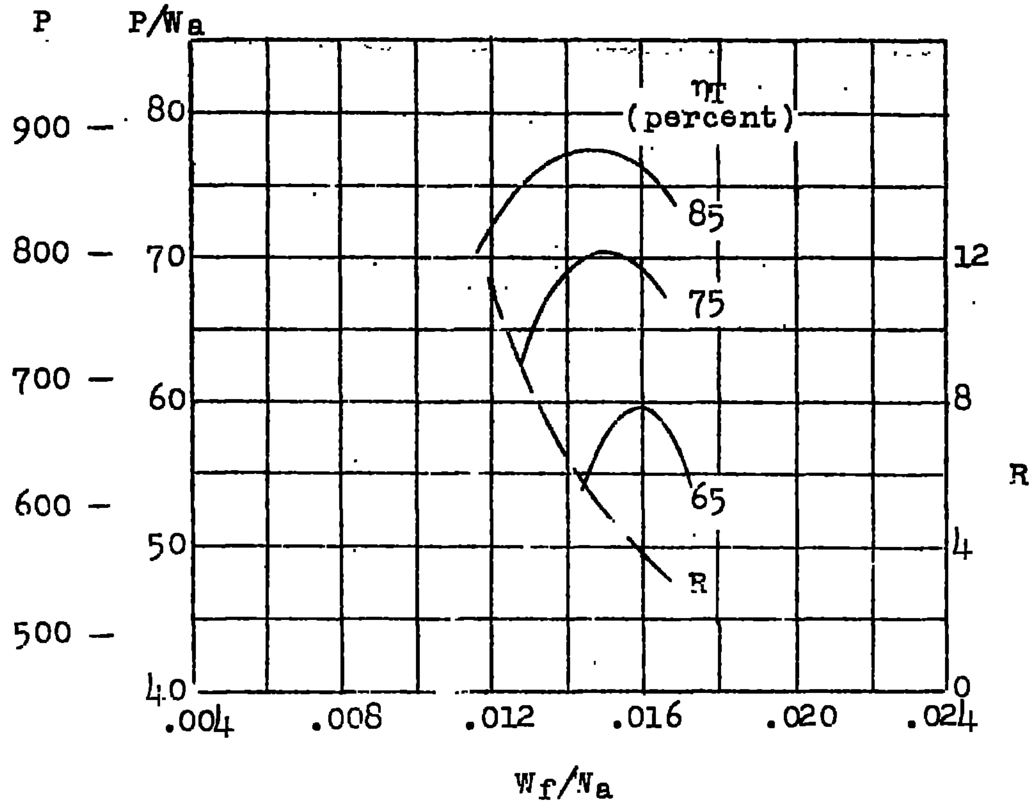
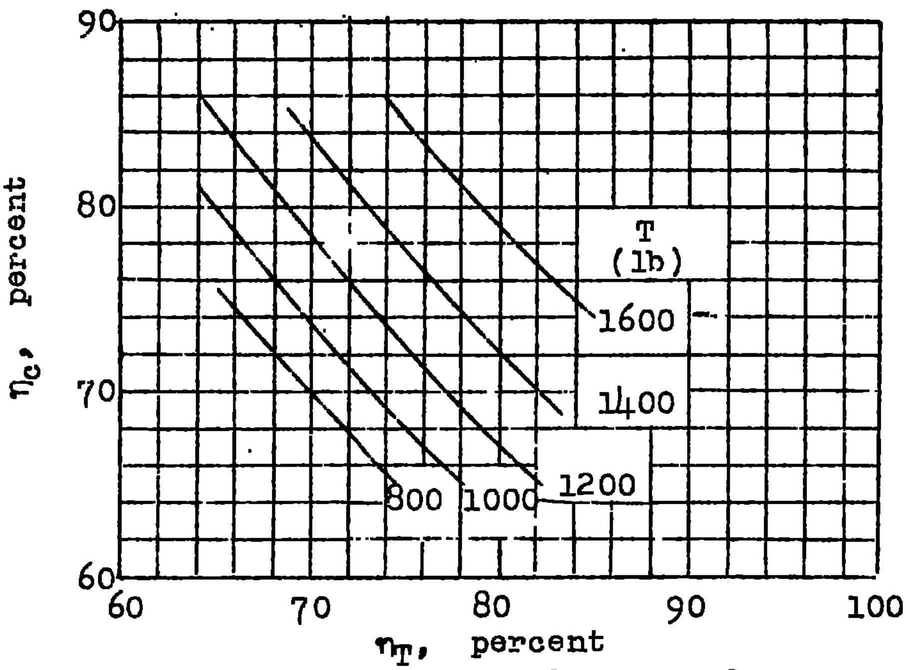


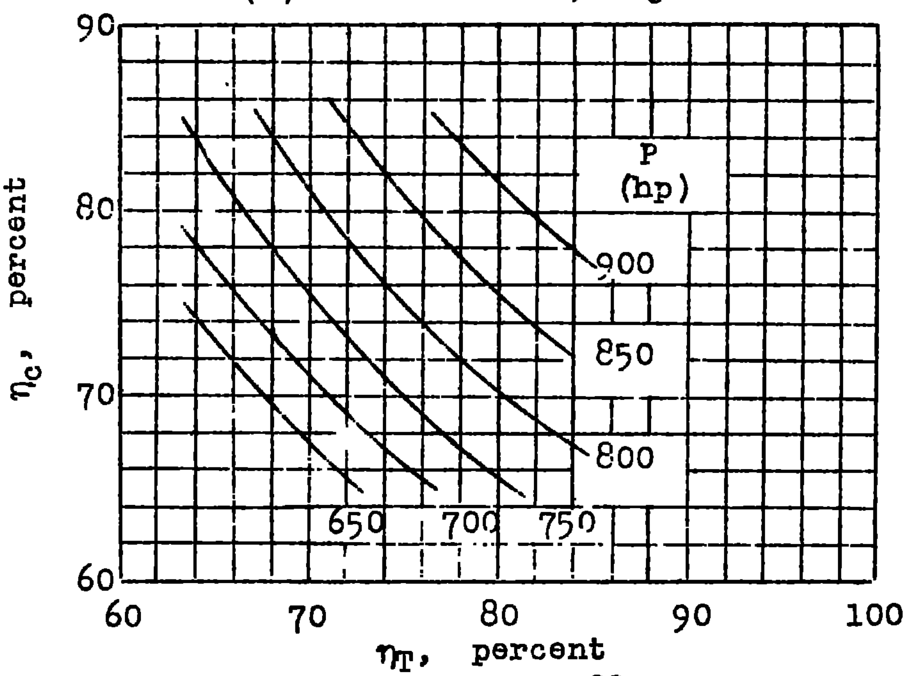
Figure 6.- Effect of fuel-air ratio on thrust power and pressure ratio. Altitude, 40,000 feet; V_o = 880 feet per second; t_{max} = 1500° F; η_c = 75 percent.

The maximum points of a number of curves of the type shown in figures 4 to 6 are plotted on coordinates of compressor and turbine efficiencies in figure 7 to show the relative importance of these two efficiencies. In this figure the axes may be interchanged with little change in the thrust or power curves, which indicates that, for all practical purposes when reasonable efficiencies are used, the thrust is equally sensitive to changes in turbine and compressor efficiencies and that the product of turbine and compressor efficiencies is more significant than either efficiency alone.

The effects of fuel-air ratio, pressure ratio, and maximum temperature on thrust and thrust power are shown in figures 8 and 9. Figure 8 shows the variation of static thrust at sea level with fuel-air ratio at each of three maximum temperatures. Lines of constant pressure



(a) At sea level; $V_o = 0$.



(b) Altitude, 40,000 feet; V_o = 880 feet per second.

Figure 7.- Relative effects of η_c and η_T on thrust and thrust power. $t_{max} = 1500^\circ$ F.

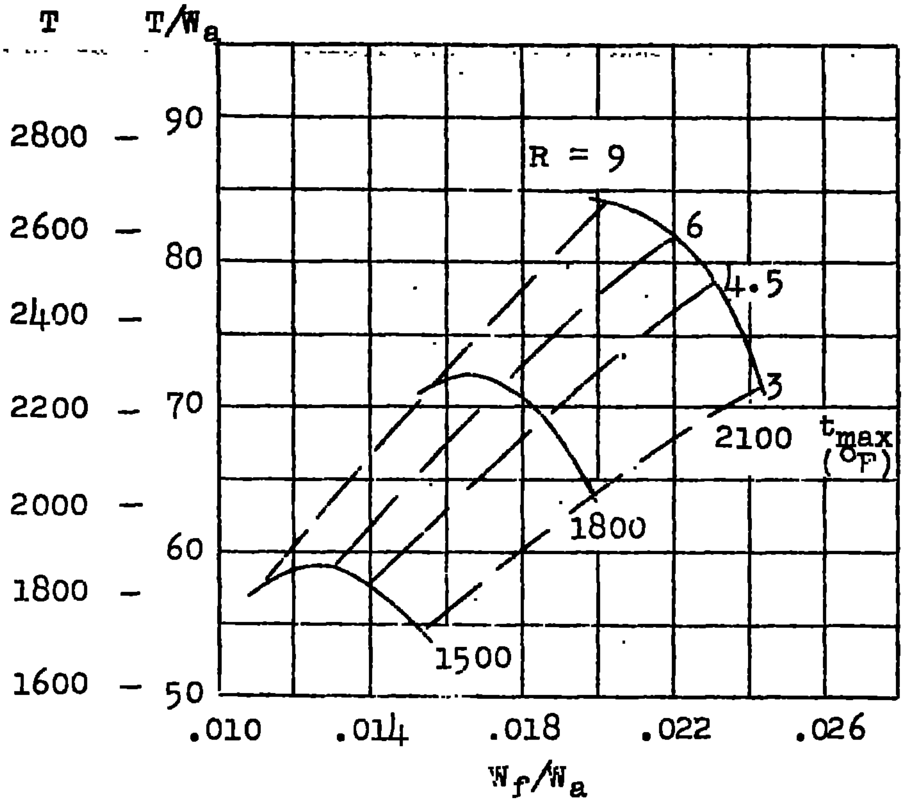


Figure 8.- Effects of fuel-air ratio, pressure ratio, and maximum temperature on thrust. At sea level; $V_o = 0$; $\eta_c = \eta_T = 85$ percent.

ratio are drawn through these thrust curves. Figure 9 is a similar plot of thrust power at high speed and high altitude. These figures indicate that, for the range of temperature considered, the maximum thrust at any altitude is nearly proportional to the difference between free-stream and combustion-chamber temperatures. At any particular temperature the thrust is more sensitive to changes in fuel-air ratio than to changes in pressure ratio.

Comparisons of many curves of the type shown in figures 4 to 9 indicate that the pressure ratio and the fuel-air ratio for a particular power condition are primarily functions of the combined turbine and compressor efficiencies and the combustion-chamber temperature. Figure 10, which shows this relationship for the maximum-power condition, is reasonably accurate for the range of flight speed and altitude considered in the present analysis.

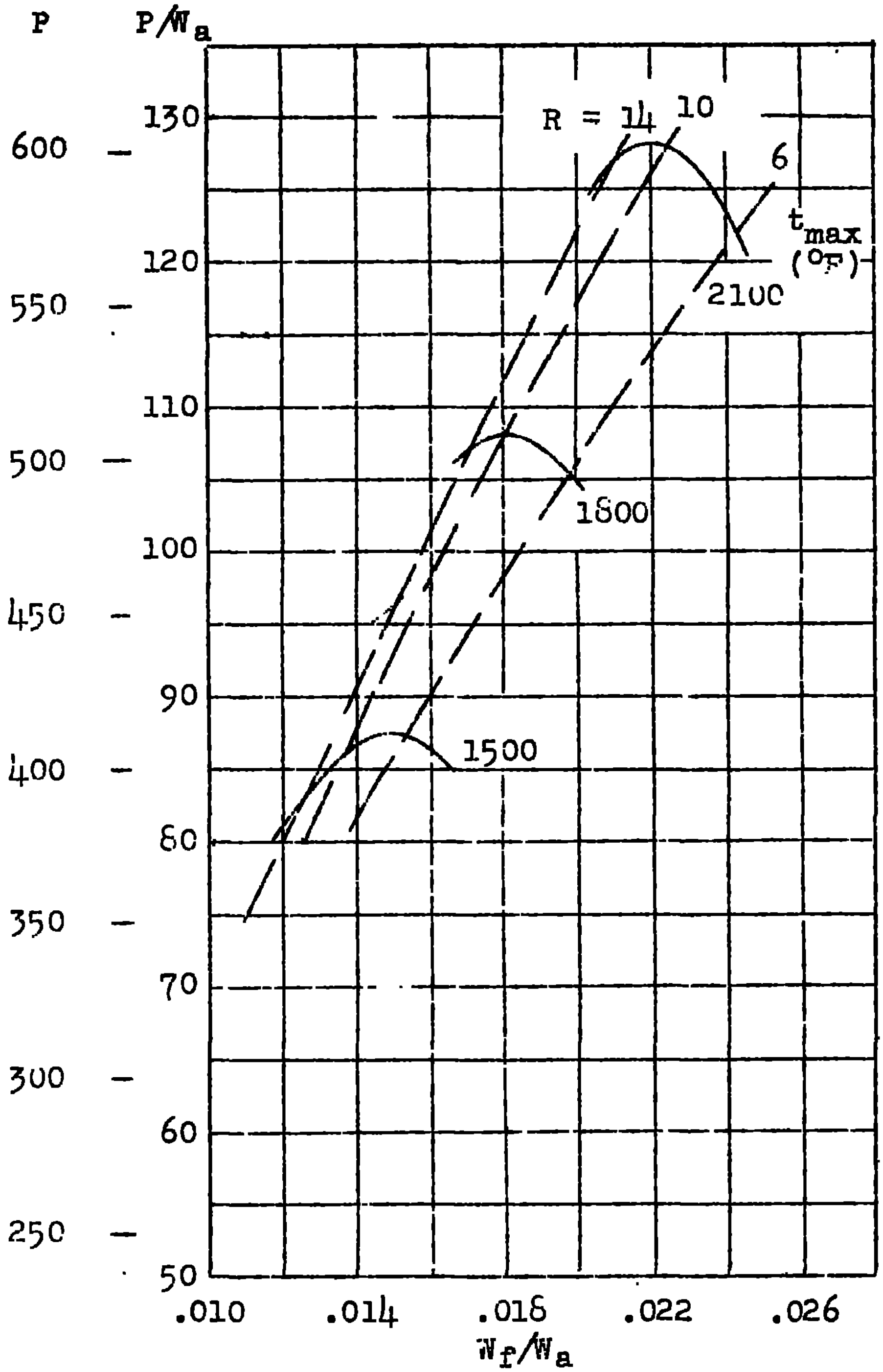


Figure 9.- Effects of fuel-air ratio, pressure ratio, and maximum temperature on thrust power. Altitude, 60,000 feet; V_o = 880 feet per second; $\eta_c = \eta_T$ = 85 percent.

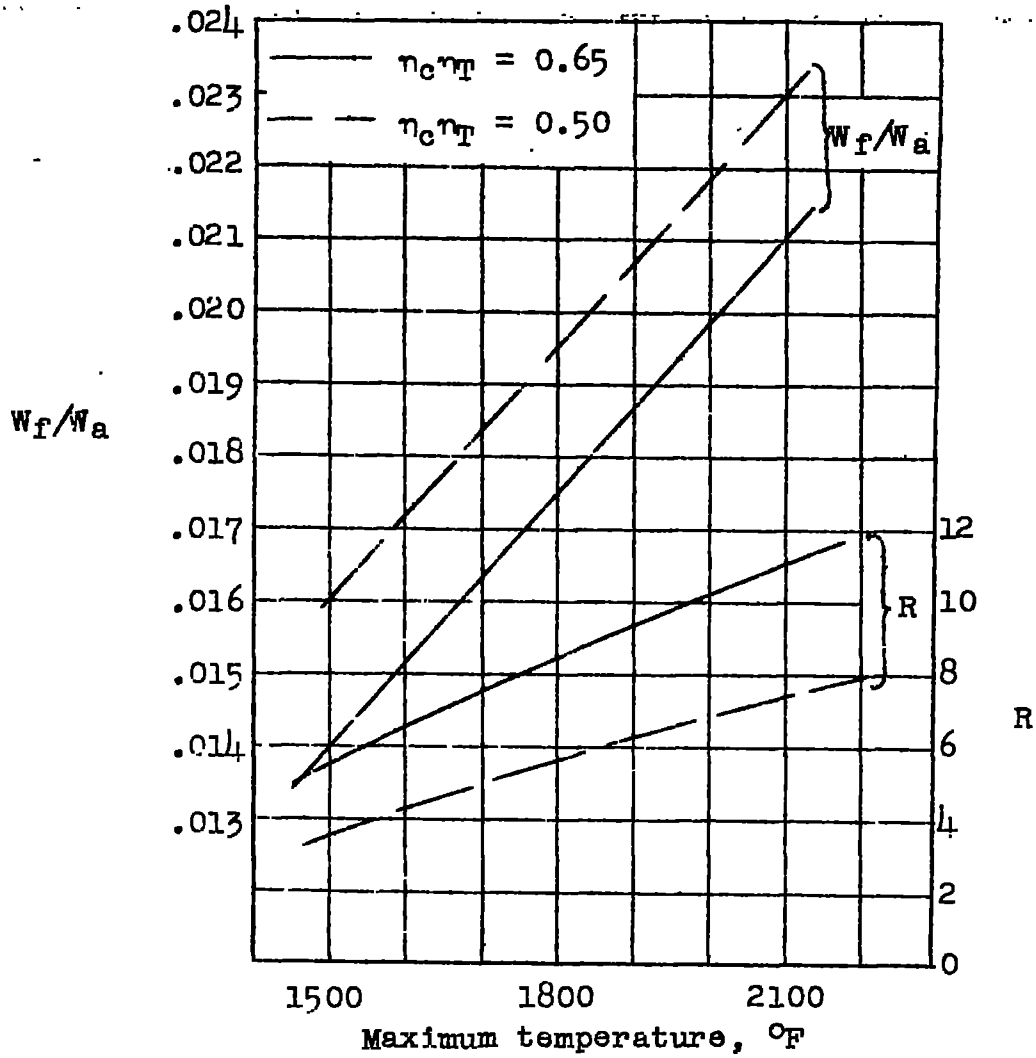
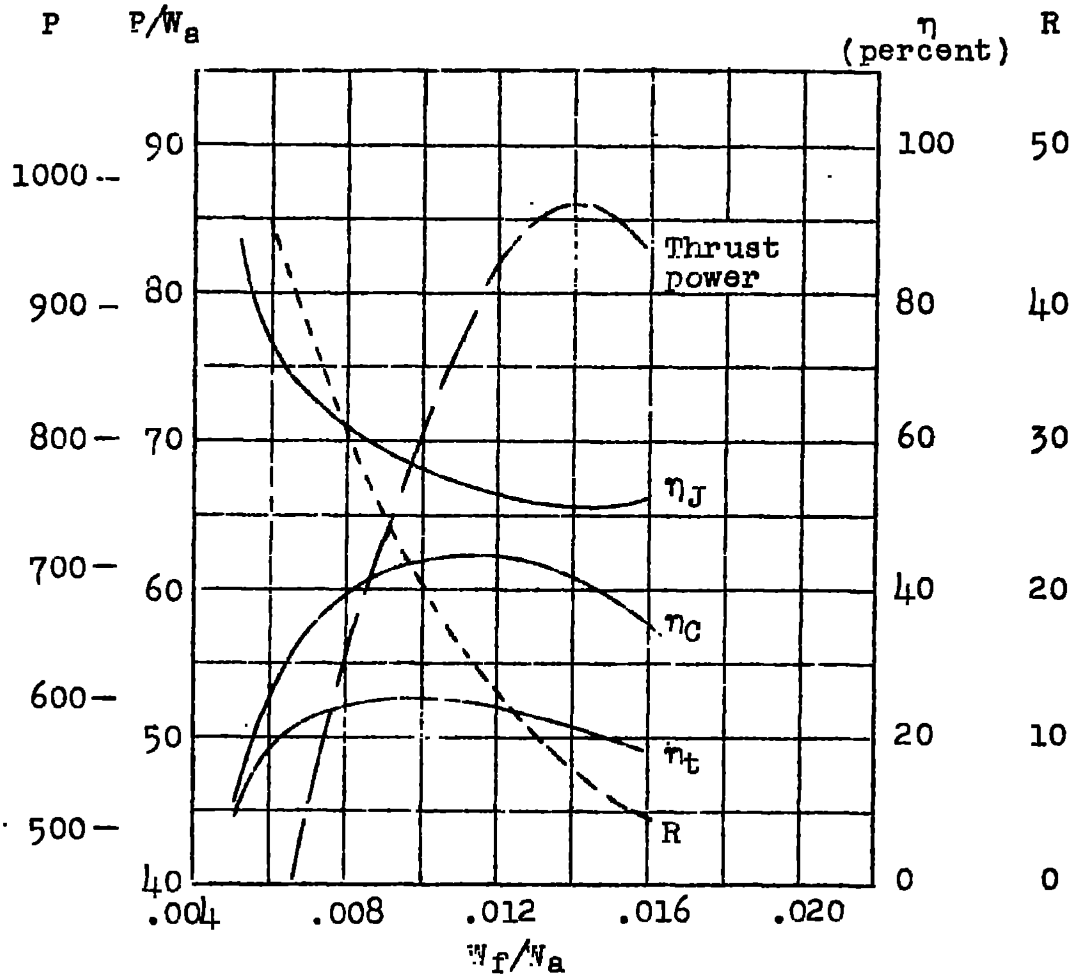


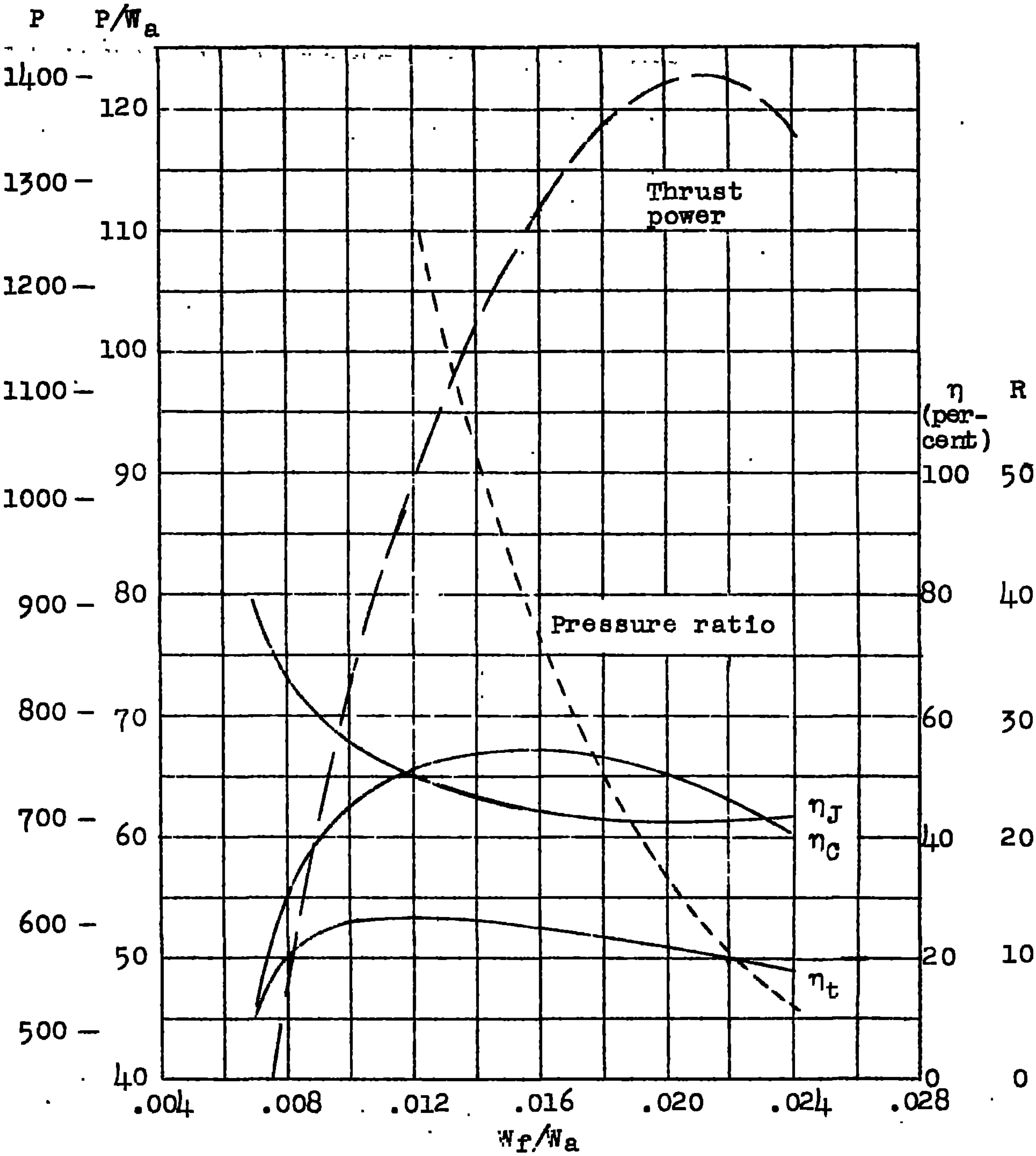
Figure 10.- Effect of engine temperature on fuel-air ratio and compression ratio. Maximum-power condition.

Figure 11 shows how the thrust power and the thermal, jet, and over-all efficiencies for 880 feet per second at 40,000 feet vary with the fuel-air ratio. Turbine and compressor efficiencies are held constant at 85 percent, and the pressure ratio is varied to keep a maximum temperature of 1500° F or 2100° F. These curves show that the maximum-thrust condition is not the condition of most economical operation. If an engine having a maximum temperature of 2100° F (fig. 11(b)) is designed to run at maximum over-all efficiency instead of maximum thrust power, the jet efficiency is improved from 42 to 51 percent, the thermal efficiency is slightly improved, and the over-all efficiency increases from 21 to over 26 percent. The thrust power, however, drops to 1000 horsepower, only 70 percent of the maximum of 1400.



(a) t_{max} = 1500° F.

Figure 11.- Changes in thermal, jet, and over-all efficiencies and thrust power with fuel-air ratio. Altitude, 40,000 feet; V_o = 880 feet per second; $\eta_c = \eta_T$ = 85 percent.



(b) $t_{max} = 2100^{\circ}$ F.

Figure 11.- Concluded.

Figure 12 shows how the thrust power and the thermal, jet, and over-all efficiencies vary with the maximum temperature for operation both at maximum thrust power and at maximum over-all efficiency. As is to be expected, the thermal efficiency increases with the temperature range of the cycle and the jet efficiency decreases with the higher velocities that accompany the high temperatures. When operation is at maximum power, an increase in maximum temperature does not cause a significant change in the over-all efficiency but the rate of fuel consumption is considerably increased. For the maximum-power condition, therefore, the net result of using a higher engine temperature is to increase the power capacity of the engine and thus to improve the power-weight ratio. When conditions of maximum over-all efficiency are specified, higher engine temperatures load to improvement in over-all efficiency as well as in engine capacity.

Calculations for other flight speeds and turbine and compressor efficiencies show that, at maximum power, the over-all efficiency is nearly independent of maximum engine temperature. The altitude effect is relatively small. Under these circumstances, curves showing over-all efficiency as a function of flight speed and the product of turbine and compressor efficiencies (fig. 13) will be approximately correct over the entire range of engine temperature and altitude under consideration. In nearly all cases the over-all efficiency will fall within the ranges indicated in the following table:

Product of turbine and compressor efficiencies	Over-all efficiency (percent)	
	880 fps	440 fps
0.4	8 to 10	-------
.5	13 to 15	4 to 6
.6	16 to 18	8 to 10
.7	20 to 22	10 to 12

Figures 14 and 15 show how the thrust power per (pound per second) of air flow varies with flight speed and altitude. Figure 14 describes operation at maximum

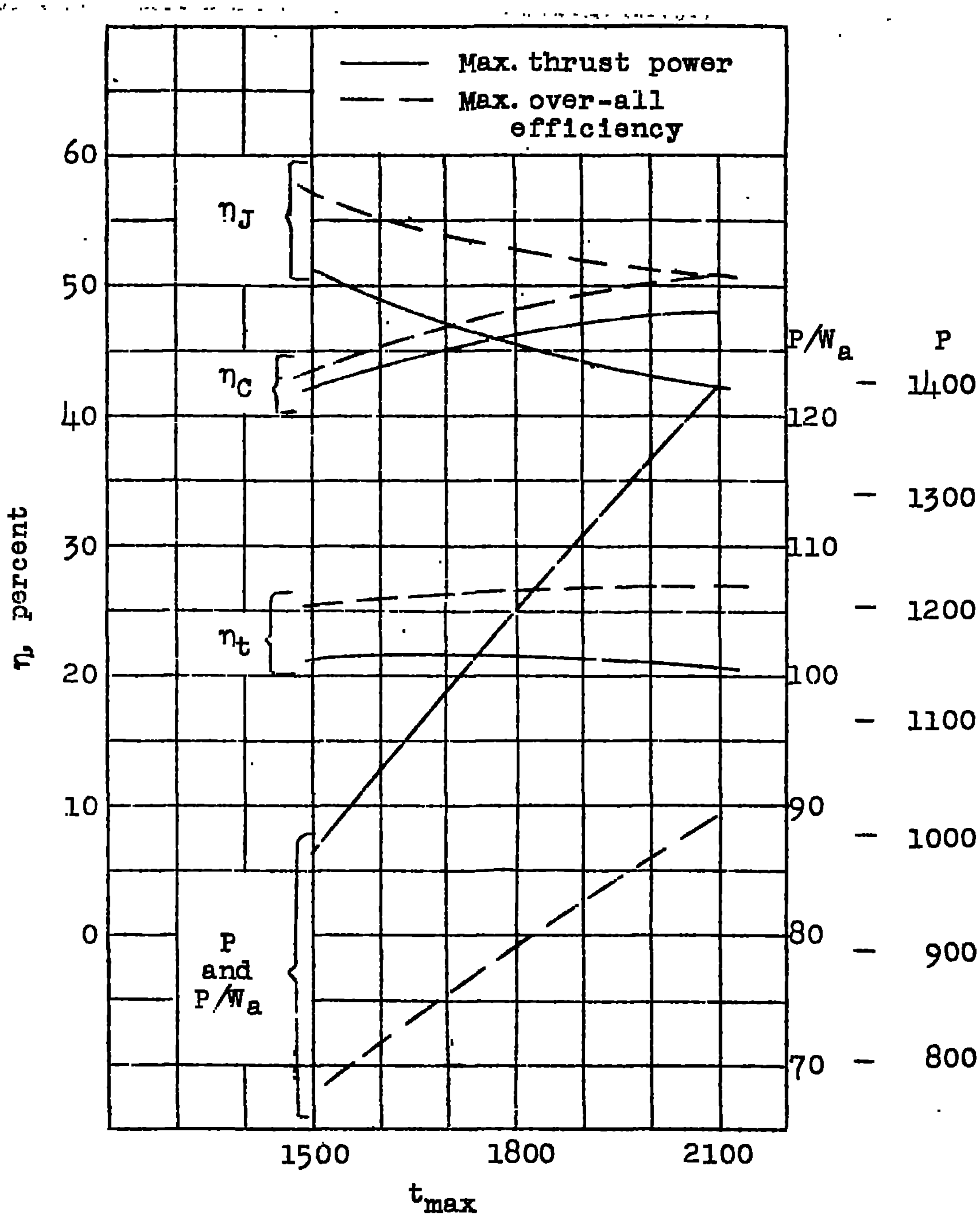


Figure 12.- Effect of temperature on power and efficiencies. Altitude, 40,000 feet; V_o = 880 feet per second; $\eta_c = \eta_T$ = 85 percent.

power and figure 15, operation at maximum over-all efficiency. The fact that the curves for altitudes of 50,000 and 60,000 feet are coincident (fig. 14) indicates that the atmospheric temperature is the only altitude effect which has a direct bearing upon the power per (pound per second) of conducted air.

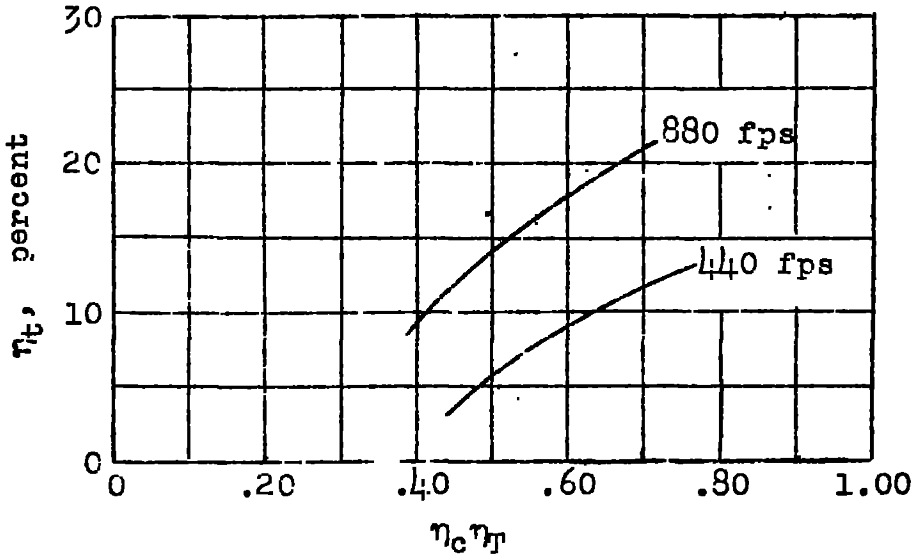


Figure 13.- Effect of turbine and compressor efficiencies and flight speed on over-all efficiency.

PERFORMANCE OF JET-ENGINE INSTALLATION

The turbine and compressor for a jet engine of the type under consideration should be so selected that the compressor torque required and the turbine torque produced exactly balance at the desired rotational speed. The blade angles must be such that both turbine and compressor operate at maximum efficiency when the design air flow is obtained.

An engine that has been designed for a particular maximum temperature, air-flow rate, and power condition (for example, maximum thrust and maximum over-all

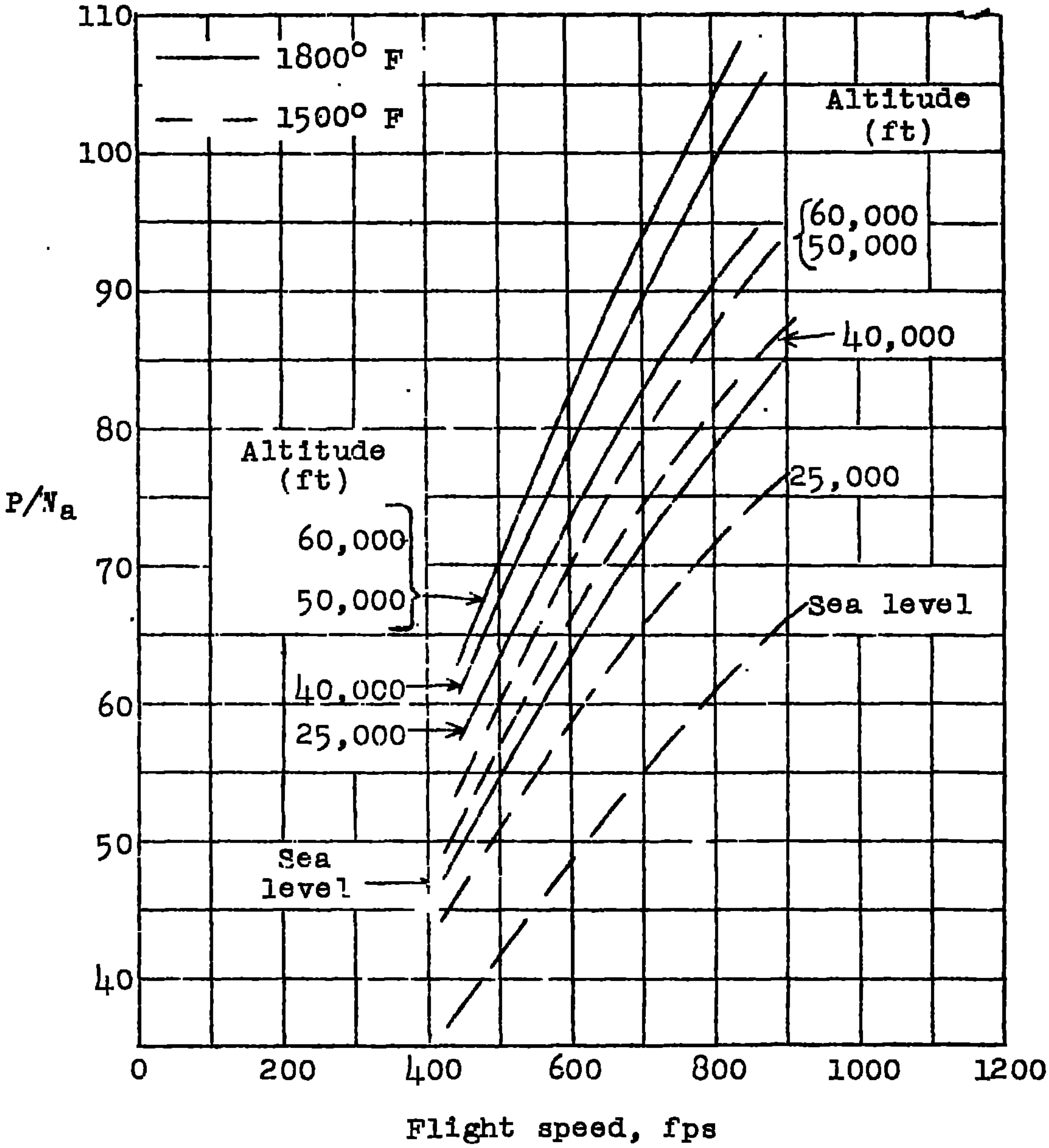


Figure 14.- Engine performance when design is for maximum power. $\eta_c = \eta_T = 85$ percent.

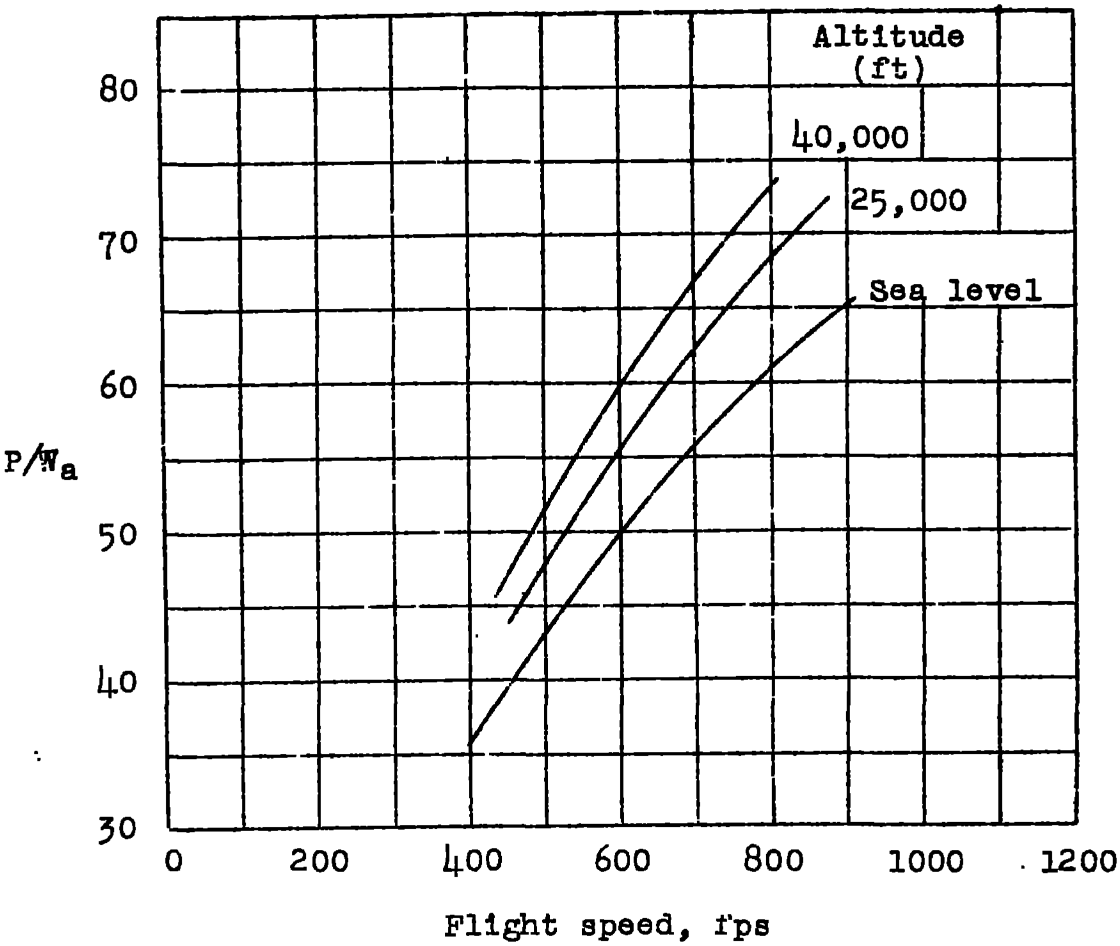


Figure 15.- Engine performance when design is for maximum over-all efficiency. $t_{max} = 1800^{\circ}$ F; $\eta_c = \eta_T = 85$ percent.

efficiency) may be operated at the same temperature and power condition over a wide range of speed and altitude with little change in turbine and compressor efficiencies - if the air-flow rate can be controlled in flight by an adjustable exit nozzle or similar means. This simple adaptability of the jet engine is discussed in appendix B. Each combination of power condition and maximum temperature, then, actually represents a single engine, the performance of which follows with only slight discrepancies the foregoing calculations. The performance calculated herein is for an airplane powered with one of the jet engines described in the preceding section.

Engine.- The turbine and compressor operate at adiabatic efficiencies of 85 percent, and a temperature of 1500° F is maintained in the combustion chamber. Operation is at the power condition of maximum thrust per (pound per second) of conducted air. The exit nozzle is of such a nature that the air-flow rate agrees with the curves in figure 2. The engine performance characteristics are shown by figure 16, in which thrust power is

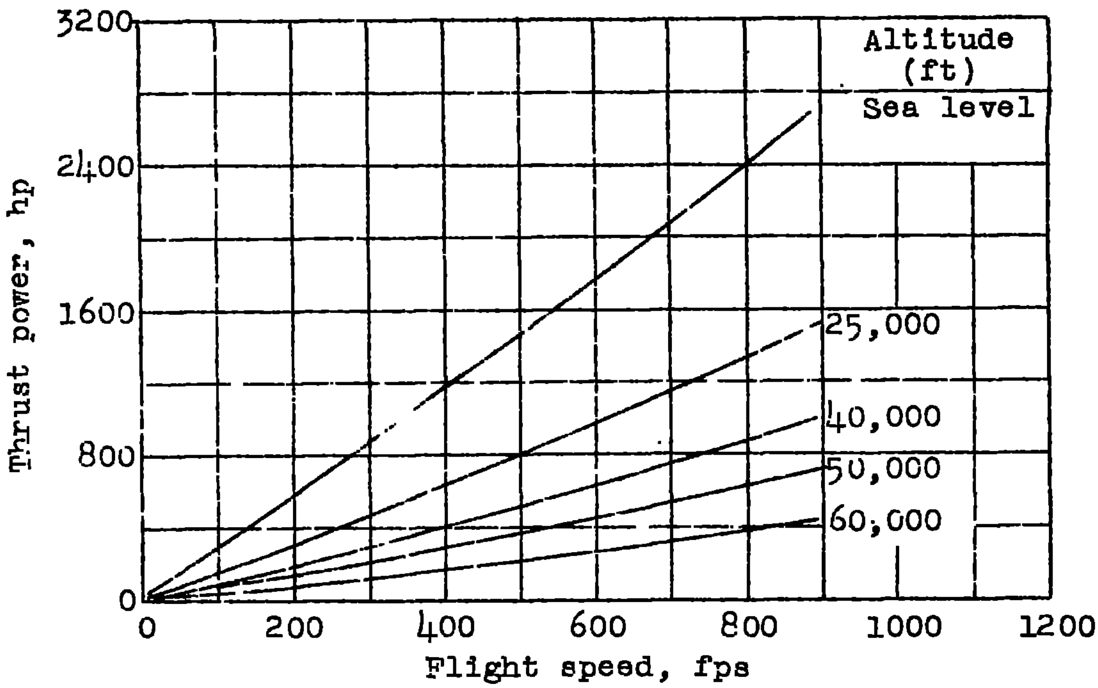


Figure 16.- Engine power output. $t_{max} = 1500^\circ$ F; $\eta_c = \eta_T = 85$ percent.

plotted as a function of flight speed. At each altitude the thrust power increases almost linearly with the flight speed, which indicates that the thrust force changes only slightly with flight speed.

Airplane.- The airplane is a small, high-speed fighter-type airplane, with a gross weight of 5400 pounds and a wing loading of 50 pounds per square foot. The lift-drag ratio for the airplane is calculated by the equation

$$\frac{L}{D} = \frac{C_L}{C_{D_o} + \frac{C_L^2}{e\pi A}}$$

where

$$C_{D_o} = 0.014$$

$$A = 5.75$$

$$e = 0.9$$

For high flight Mach numbers this ratio is divided by the correction factor for C_D shown in figure 17,

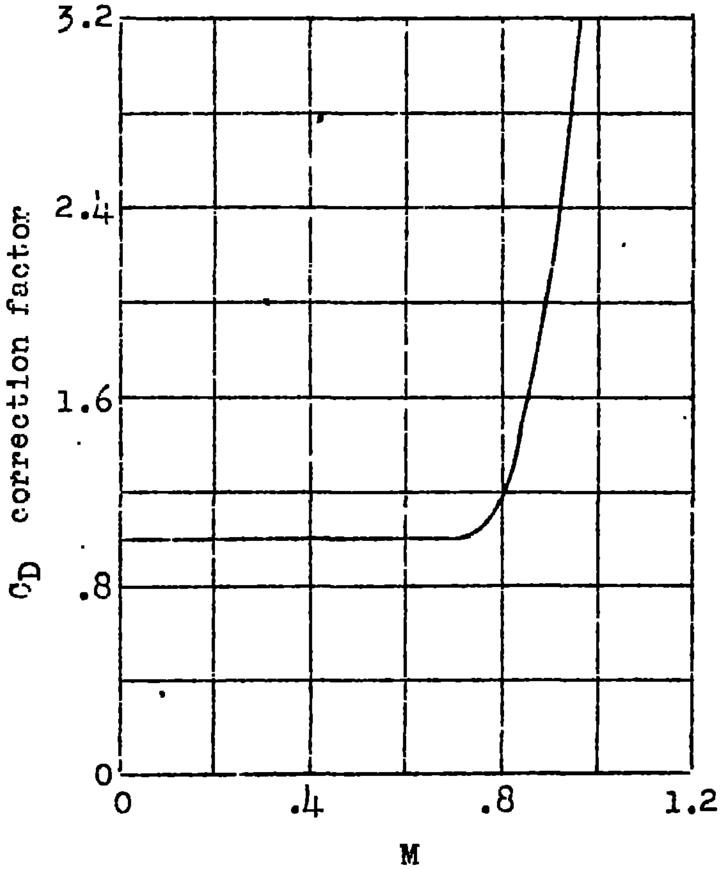


Figure 17.- Mach number correction for drag coefficient. (From unpublished data.)

which was obtained from unpublished data. The resulting airplane power requirements for level flight are shown in figure 18.

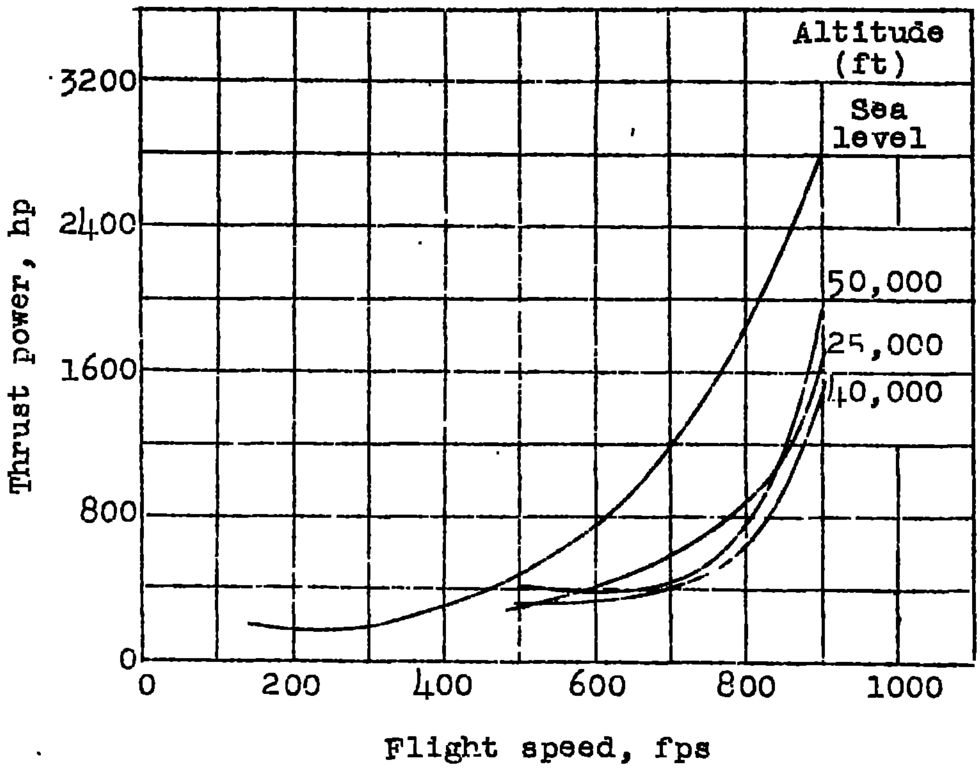


Figure 18.- Power required by airplane for level flight.

Calculations of performance.- In order to calculate speed and rate of climb, the power required by the airplane for level flight at a particular altitude (fig. 18) can be plotted on the same graph with the power output of the engine at the same altitude (fig. 16). The intersection of the two curves will indicate the level-flight speed for the particular altitude-engine-airplane combination under consideration. For flight speeds less than that obtained in level flight, the excess of power available over power required may be used for climb.

The variation in airplane level-flight speed with altitude is shown in figure 19. The fact that the speed

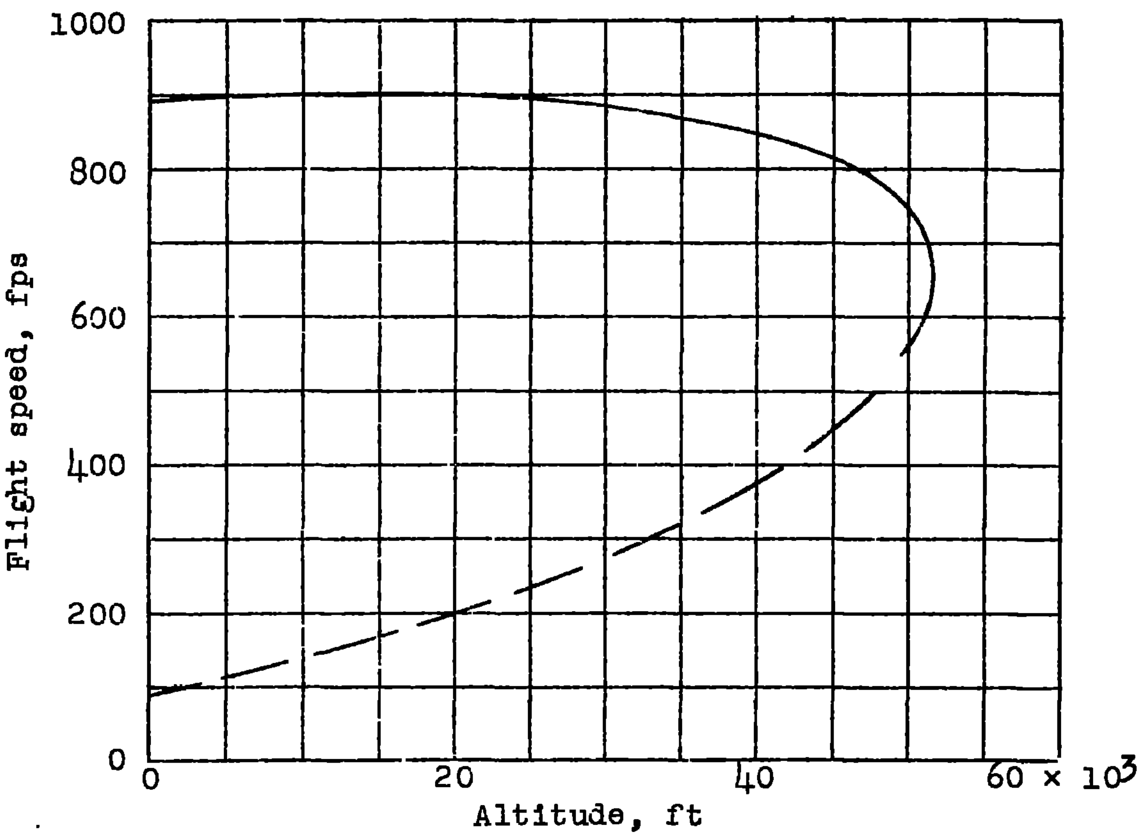


Figure 19.- Effect of altitude on level-flight speed of jet-propelled airplane. $t_{max} = 1500^{\circ}$ F; $\eta_c = \eta_T = 85$ percent; W = 5400 pounds; S = 108 square feet.

does not increase with altitude is due to the assumed effect of the Mach number on the drag. As the altitude increases, sonic velocity decreases and the Mach number effect on the drag is evident at lower flight speeds. If the airplane were l rger or the engine smaller, the flight speeds would be lower but would increase slightly with altitude in the usual manner.

In figure 20 the maximum rate of climb is shown as a function of the altitude. The discontinuity in the slope of this curve occurs at the altitude above which the temperature is assumed to be constant.

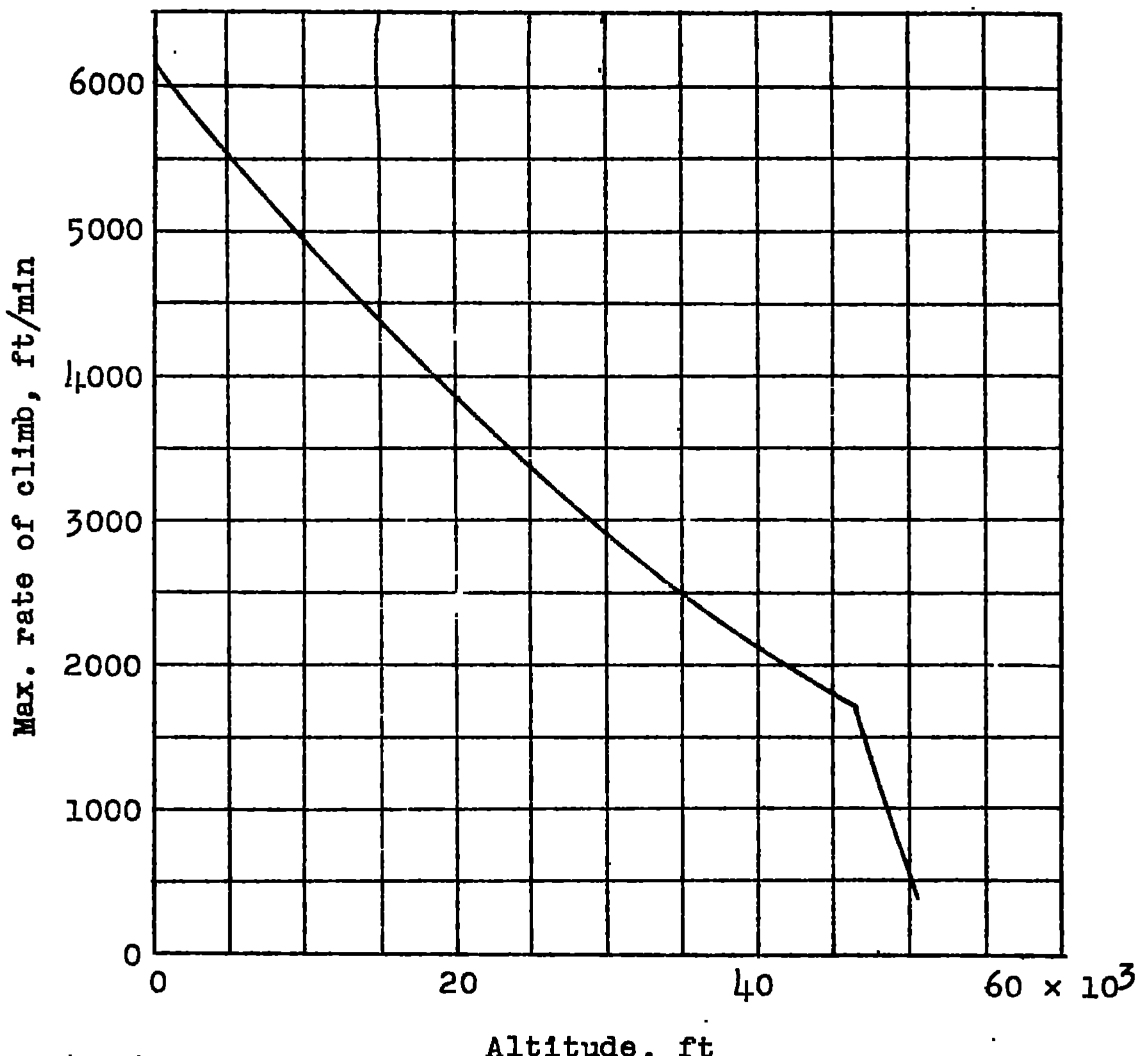


Figure 20.- Effect of altitude on maximum rate of climb of jet-propelled airplane. $t_{max} = 1500^{\circ}$ F; $\eta_c = \eta_T = 85$ percent.

These performances are only for a particular combination of airplane and jet engine. Curves of thrust power against speed for various altitudes may be drawn for an engine having any combination of turbine and compressor efficiencies and maximum temperature, and on these engine curves may be superimposed the performance curves of any airplane. For an engine of different size, having flow properties similar to those of the engine described, the fuel consumption and thrust power vary with the square of the engine diameter.

CONCLUDING REMARKS

For each assumed maximum engine temperature in this performance analysis of jet-propulsion systems, particular attention has been given to only two types of cycle: the type giving maximum thrust power per (pound per second) of conducted air and the type giving the highest over-all efficiency of conversion of fuel energy into thrust power. When the turbine and the compressor are selected for engine operation at maximum over-all efficiency, the over-all efficiency is about $1\frac{1}{5}$ times and the thrust power is about three-fourths of the corresponding values when operation is at maximum thrust power.

The maximum thrust-power output at a particular altitude is approximately proportional to both the flight speed and the temperature difference between the free stream and the combustion chamber.

The efficiencies of the turbine and the compressor are about equally important in determining the engine performance. For reasonable values of each, the product of these efficiencies may be considered a good index of the attainable performance.

The following table shows the relation between the product of turbine and compressor efficiencies and the over-all efficiency for two flight speeds. Although based only on cycles giving maximum thrust, the table applies to all altitudes and engine temperatures considered herein.

Product of turbine and compressor efficiencies	Over-all efficiency (percent)	
	880 fps	440 fps
0.4	8 to 10	--------
.5	13 to 15	4 to 6
.6	16 to 18	8 to 10
.7	20 to 22	10 to 12

The fuel-air ratios and the pressure ratios for the maximum-power cycles are determined by the maximum allowable gas temperature and the product of turbine and compressor efficiencies. The approximate magnitudes of these ratios for three gas temperatures are shown in the following table:

Maximum temperature (°F)	Pressure ratio	Fuel-air ratio
1500	5 to 6	0.015 to 0.013
1800	8 to 9	.019 to .016
2100	10 to 12	.022 to .020

In this table the product of turbine and compressor efficiencies is constant at 0.65. A similar table for an efficiency product of 0.50 would show fuel-air ratios 0.001 to 0.002 higher than and pressure ratios about two-thirds of those shown.

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Langley Field, Va.

APPENDIX A

SYMBOLS

a	cross-sectional area of duct, sq ft
A	aspect ratio
c	sonic velocity, fps
C_D	drag coefficient
C_{D_o}	profile-drag coefficient
C_L	lift coefficient
d	diameter, ft
D	drag, lb
e	span efficiency factor
L	lift, lb
M	Mach number (V_o/c)
n	rotational speed, rps
p	pressure, lb/sq in.
P	thrust power, hp
Q	volume rate of flow of air, cu ft/sec
R	ratio of static pressure after compressor to static pressure before compressor
S	wing area, sq ft
t	temperature, ^{o}F
t_{max}	maximum gas temperature, ^{o}F
T	thrust, lb
v	specific volume, cu ft/lb
V	velocity of air through duct, fps

V_J velocity of air through exit nozzle, fps

V_o flight speed, fps

W gross weight of airplane, lb

W_a weight rate of charge-air flow, lb/sec

W_f rate of fuel consumption, lb/sec

η_c adiabatic efficiency of mechanical compression, ratio of isentropic to actual enthalpy increase for a particular pressure rise

η_C thermal, or cycle, efficiency

$$\left(\frac{\text{Heat input - Heat rejected}}{\text{Heat input}}\right)$$

η_J propulsive efficiency of the air jet $\left(\dfrac{2V_o}{V_o + V_J}\right)$

η_t over-all efficiency of conversion of fuel energy into thrust power

η_T adiabatic efficiency of turbine, ratio of actual to isentropic enthalpy decrease for a particular pressure drop

ρ air density, lb/cu ft

APPENDIX B

CONDITIONS AND ASSUMPTIONS

The conditions and assumptions used in the foregoing analysis are listed herein. Some explanation is given when necessary.

Army summer air is used exclusively. The thermal-air jet engine operates on the same cycle as a ducted cooling system; the atmosphere customarily used in calculations for cooling equipment is therefore used for the jet engine. This use of Army air gives a somewhat conservative estimate of engine performance.

Uniform temperature, pressure, and velocity exist over any cross section of air duct in the engine. Air velocity throughout the engine is kept so low that deviations from this idealized condition are of little significance.

No heat is lost from the engine by conduction, and all air flow is frictionless except in the turbine and compressor. These idealizations invalidate none of the conclusions, since the duct friction losses are negligible with the velocities used and the conduction heat losses may be taken care of by using a slightly higher fuel rate. It may be possible in some cases to improve the performance of a jet-engine installation by decreasing the duct area and therefore the frontal area of the engine and by taking some friction loss in the ducts.

The weight flow of charge air is maintained proportional to the stagnation density of the charge air. The following discussion indicates the reasons for this assumption and some of its results. With this air-flow control, the velocity of the air entering the compressor is practically constant. When the engine is operating at maximum thrust power and a particular maximum temperature, the velocity of air entering the turbine is constant to about ±7 percent, for flight speeds of 440 to 880 fps at altitudes from sea level to 60,000 ft. The continuity equation for the conducted air is

$$\rho Va = W_a$$

The entrance area and velocity remain constant for both compressor and turbine. The weights of the air flowing through the compressor and the turbine are essentially equal and thus vary at the same rate. The density of the air entering the compressor and the turbine, therefore, varies at the same rate. Furthermore, both the torque output of the turbine and the torque required to run the compressor at constant speed are proportional to the density of the conducted air. The compressor torque required and the turbine torque produced, therefore, vary at the same rate and remain balanced at a constant rotational speed over a wide range of altitude and flight speed.

Because the assumed control of air flow makes it possible to operate the compressor at constant Q/nd^3, the power put into a pound of air by the compressor is constant for all altitudes and flight speeds. The pressure ratio is greater at high altitudes, then, than at low altitudes and is slightly greater at low flight speeds than at high flight speeds. In fig. 21 the

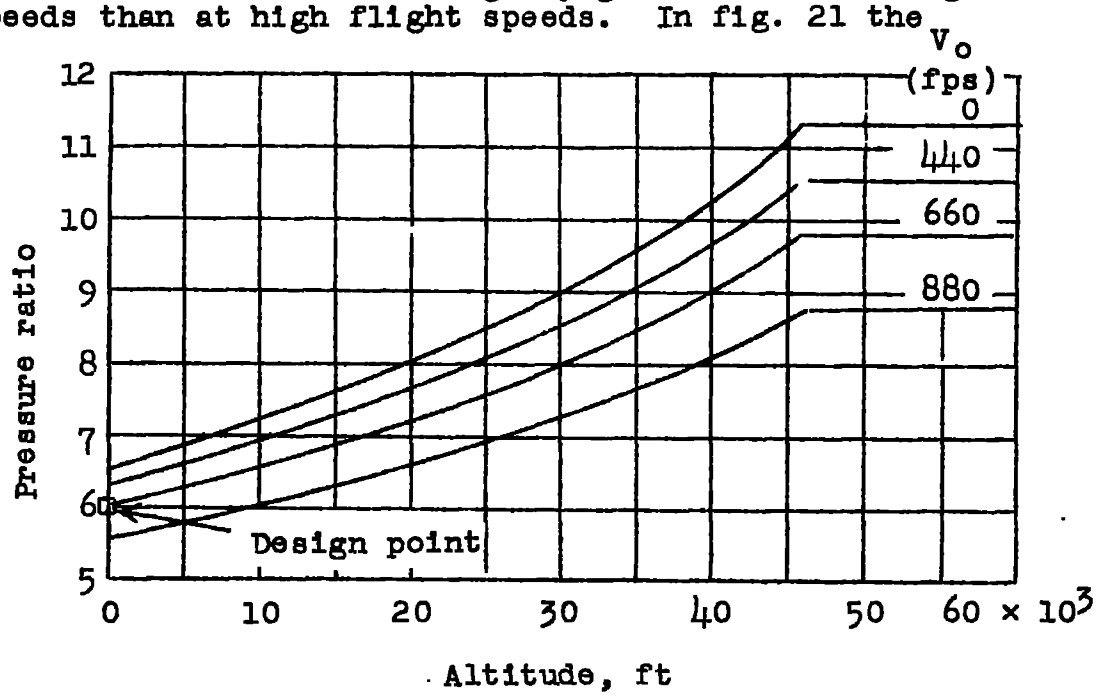

Figure 21.- Effect of altitude on pressure ratio over an axial compressor. Constant rotational speed and air volume.

pressure ratio is shown as a function of altitude and flight speed for an axial compressor operating at constant Q/nd^3 and an adiabatic efficiency of 85 percent. This variation in pressure ratio for a particular compressor causes an engine designed for maximum power at a particular altitude and speed to operate at maximum power over a wide range of altitude and speed.

The heat value of the fuel is 19,700 Btu/lb, and combustion is assumed complete at the turbine entrance.

Losses in total pressure occur only in the compressor and the turbine, and mechanical losses are allowed for in the efficiencies of the compressor and the turbine.

Because of the great excess of air, the properties of the exhaust gas are assumed to be the same as those of air, but allowance is made for the increase in the weight of the conducted air due to the addition of fuel.

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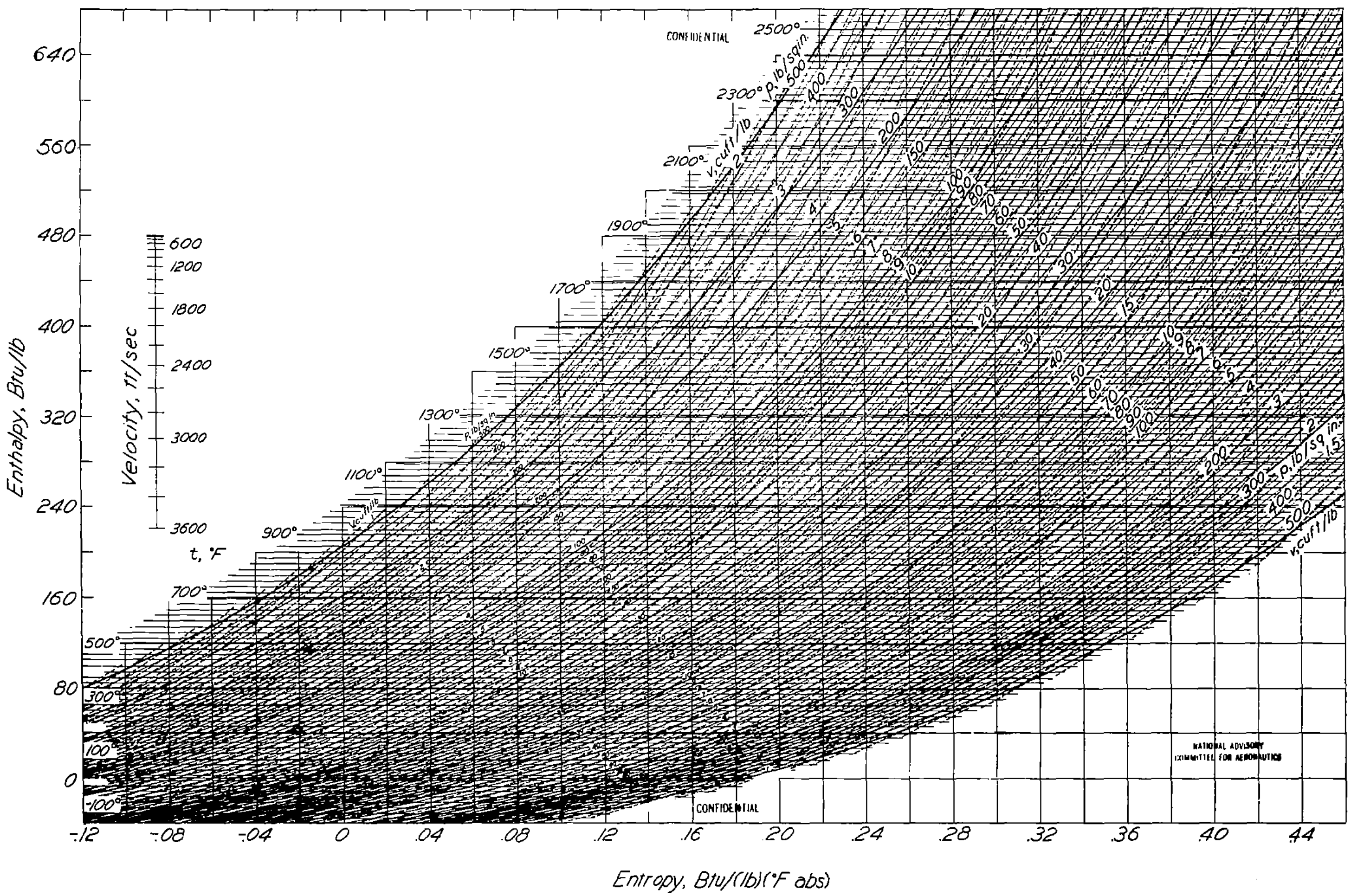

Figure 1. - Thermodynamic properties of air.
(Transformed from reference 2.)